

# OFF-ROAD AXLE DETECTION SENSOR (ORADS)



PB99-112039

## OCCLUSION FEASIBILITY STUDY State Job No. 14669(0)

### Final Technical Report

PS 97-03  
Agreement 8525

Sponsored by:  
Ohio Department of Transportation (ODOT)  
Office of Research and Development  
Columbus, Ohio 43216

27 August, 1997

### *Research, Development and Technology Transfer Program (RD&T)*

**Reference:** Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

**Disclaimer:** The contents of this report reflect the views of the author(s) who is(are) responsible for the facts and the accuracy of data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

Authored by:  
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**PREFACE**

Spectra Research, Inc. (S\*R), a high technology business based in Dayton, Ohio, provides advanced research and development services for government and industry. The company specializes in high quality engineering design, development, and testing. Our expertise includes laser and infrared systems, electromagnetic sensors, training systems, electronic warfare avionics, medical sensor research, applied system design, and software support.

S\*R is currently developing a family of low-cost, non-intrusive, lane monitoring systems to measure and classify vehicular traffic over multiple lane roadways. The non-intrusive nature permits portable or permanent set-up on the road shoulder without costly construction, maintenance, traffic disruptions, and hazardous situations for highway personnel. Several models are being developed to facilitate remote monitoring, data storage, GPS tagging, and low cost features. Prototype units are scheduled for delivery mid-1998.

The S\*R Lane Monitoring System (LMS) represents a major achievement in traffic engineering through portability, low cost, easy set-up, and elimination of hazards to motorists and highway maintenance personnel.

S\*R appreciates the contributions and support of our Ohio Department of Transportation (ODOT) monitor, Mr. Tony Manch, 614-466-3075.

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**ACKNOWLEDGMENTS**

Spectra Research, Inc. would like to acknowledge the efforts of Dr. Gordon Little, University of Dayton Research Institute (UDRI), for providing the statistical analysis of traffic variation as discussed in Appendix A of this report.

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**EXECUTIVE SUMMARY**

**Off-Road Axle Detection Sensor (ORADS) - Occlusion Feasibility Study  
State Job No. 14669(0)**

The work accomplished under this initiative is in direct relation to the development effort proposed by Spectra Research, Inc. (S\*R) for an "Off-Road Axle Detection Sensor (ORADS)". The feasibility study was performed to investigate potential occlusions that may arise from the use of a laser-radar (LADAR) based sensor configuration. This feasibility study was suggested to determine any potential risk in the development.

S\*R was awarded a contract to perform video analysis work over a six month period. S\*R performed video tests to visually inspect situations under which occlusion may occur during peak, unidirectional traffic flow on a highly populated, multiple lane interstate. The test site was selected by ODOT representatives, I-275 northbound at exit 46 during peak traffic times (4-6 p.m.). Data was collected for approximately one hour using two video cameras. Camera 1 was used to record on-coming traffic for lane and volume data. Camera 2 was positioned to act as the LADAR sensor to provide axle count and occlusion data.

The results of this effort show that across a multiple lane roadway exhibiting high volume traffic flow, the aggregate probability of axle occlusion is 4.21%. These results were anticipated and conform to the error requirements (<10%) identified by ODOT officials. Recommendation is made for further funding of the ORADS Phase II development.



**OFF-ROAD AXLE DETECTION SENSOR (ORADS) - OCCLUSION FEASIBILITY STUDY  
STATE JOB NO. 14669(0)  
FINAL TECHNICAL REPORT**

## **1. INTRODUCTION**

On April 17, 1996, Spectra Research, Inc. (S\*R) submitted a proposal entitled "Off Road Axle Detection Sensor (ORADS)" to the Ohio Department of Transportation (ODOT) for review. This proposal described the Phase I development of the laser trip-wire sensor and its application to the proposed ORADS LADAR design. ODOT's review of the proposal and subsequent response prompted a meeting at ODOT facilities on June 28, 1996. The main concern at this meeting was resolution of the possible occlusion problem associated with the ORADS design. A feasibility study was suggested as the best means to eliminate any potential risk in the development effort.

S\*R subsequently submitted a revised proposal on July 12, 1997 entitled, "Off-Road Axle Detection Sensor (ORADS) - Occlusion Feasibility Study". S\*R proposed to perform two tests to eliminate the risk associated with the potential occlusion problem prior to establishing a firm ORADS design in Phase II. Test one was a video analysis to visually inspect situations under which occlusion may occur, and the second test was a software simulation to identify probability of occlusion.

S\*R was awarded a contract on November 11, 1996 to perform the video analysis work proposed for this study<sup>1</sup>. This contract was funded for \$12,651.00 extending over a six month period. The contract was subsequently extended an additional 6 months, with completion scheduled for November 11, 1997.

### **1.1 BACKGROUND OF WORK**

On April 6, 1995, Spectra Research, Inc., (S\*R) completed a U.S. Air Force sponsored Phase I Small Business Technology Transfer (STTR) program using military laser technology to define, construct, and demonstrate a low cost portable traffic monitoring system. This system was designed to be integrated into the current traffic monitor inventory of the Ohio Department of Transportation (ODOT). A proof of concept laser trip-wire system was demonstrated to ODOT in October of 1995 at a test site just west of Columbus, Ohio (westbound I-70).

This demonstration proved that a low power laser beam positioned just above the road surface and aimed at passing vehicle tires could reflect enough energy to detect axles with lane discrimination across three lanes. The hardware used in this demonstration contained a transmitter and a masked, three-channel receiver. This receiver and transmitter were offset by approximately five feet. To accommodate ODOT's requirement for a smaller, more compact package, S\*R adapted the laser triangulation tripwire to a laser transmitter and receiver contained in the same package. The LADAR approach achieves lane discrimination by timing the reflected return signal from the vehicle tire or wheel. However, in both approaches, when using a single laser beam directed across a multiple lane highway, the vehicle in the lane closest to the laser source may mask or occlude the axle(s) of the vehicle(s) in the subsequent lane(s).

### **1.2 THE OCCLUSION PROBLEM**

The Phase II S\*R ORADS portable traffic monitor will be located on the side of the roadway with the laser beam aligned perpendicular to the traffic flow. When considering multiple lanes of traffic (2+), Lane 1 corresponds to the lane closest to the monitor, Lane 2 is the lane directly adjacent to Lane 1, and so on.

The design requires the laser beam to illuminate the vehicle wheel or tire long enough to provide a reflected signal return to the receiver. Once the reflected signal is received, the pulses are translated into lane information and axle count. To occlude an axle from being counted, the wheels of the vehicle in the

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<sup>1</sup> ODOT Agreement 8525, State Job Number 14669(0) entitled "Off-Road Axle Detection Sensor (ORADS) - Occlusion Feasibility Study".

nearest lane must completely mask the wheel(s) of a vehicle(s) in the outer lane(s) simultaneous to the time the wheels pass through the laser beam. Lane 1 will always provide an accurate axle count because no interruption to the laser beam should occur under normal conditions. Vehicle wheels in Lane 2 can only be masked by wheels in Lane 1. The lane(s) subsequent to 1 and 2 can be masked by any combination of axles in the lane(s) previous to it. Since wheel sizes, wheel bases, number of axles, and vehicle speeds will vary in all lanes, the probability of complete occlusion in Lane(s) 2+ appears to be low. However, if occlusion does occur frequently, then the traffic monitor accuracy will be affected.

The current TraciCOMP® III, Model 241<sup>2</sup> portable traffic monitoring unit is capable of 90% accuracy. This accuracy is acceptable to ODOT. The portable ORADS traffic monitor developed by S\*R must achieve the same or better accuracy to be accepted. In this study, S\*R has determined how often occlusion occurs during a typical monitoring period and how it would affect axle count accuracy. **The results of this study indicate that the S\*R Phase II ORADS system will have an accuracy equal to or better than the current traffic monitors, thus the risk factor for the Phase II development is greatly reduced.**

## 2. RESEARCH OBJECTIVE

The primary objective of this feasibility study was to eliminate occlusion as a risk factor during the design and development of the Phase II ORADS traffic monitoring system.

Two tasks were identified by S\*R for this study.

1. Collect and analyze video data of actual traffic conditions.
2. Document results.

The initial objective was to be accomplished by collecting and analyzing video data procured from the westbound, I-275 East, Exit 46 ramp between the hours of 4:00 p.m. and 6:00 p.m. This time frame was requested and is representative of peak traffic volume at that location. This test was limited to the function of traffic volume with lane discrimination.

The final report discusses the results and conclusions of the study and has been prepared and submitted in accordance with all data collected during the test.

## 3. DESCRIPTION OF RESEARCH

### 3.1 SITE CONDITIONS

The occlusion test was conducted on March 11, 1997 at a site located on I-275 East, just before Exit 46 (north of Cincinnati). This site provided the multiple lane, high speed, high density traffic required for this study. The test was conducted during peak traffic between 4:33 p.m. and 5:45 p.m. The test incorporated four lanes of traffic (3 through lanes, 1 exit ramp). Average traffic speed for all four lanes was estimated to be between 55 mph to 70 mph. Video data was not degraded by any traffic discrepancies or slow downs. All traffic monitored during this time period was relatively constant for all four lanes.

### 3.2 TEST SETUP

The clocks on both cameras were synchronized to indicate current date and time in the video. The shutter speeds used were defined from previous video data collection experiments and permitted high quality resolution for frame-by-frame analysis of the data.

Oncoming traffic volume was monitored with a VHS-c recorder (Camera 1) angled approximately 45° to the road surface. This camera produced traffic data for lane count and vehicle classification. All four lanes could be monitored with this camera. A shutter speed of 1/4000 was used to allow for light filtering and

<sup>2</sup> A product of Peek Traffic, Inc. 1500 N. Washington Boulevard, Sarasota, FL 34236.

slow-motion playback. Data collection from this camera terminated after approximately 53 minutes due to insufficient battery life.

A second VHS-c recorder (Camera 2) was used to function in the same manner as the laser tripwire. It was located on the road shoulder, approximately 10 feet from the near lane. Camera 2 was leveled on a wooden board and placed approximately 12 inches above the surface of the road shoulder, perpendicular to the flow of traffic. The camera was focused along a patch line that stemmed across the entire road surface. This patch was used as a reference point for this study. This height was required to provide a line of site for the far lanes due to road crown. This camera was used to monitor possible instances of occlusion. A shutter speed of 1/10000 was used to allow for high quality slow motion and frame-by-frame playback. This camera produced approximately 72 minutes of data.

### 3.2.1 DATA ANALYSIS

S\*R engineers analyzed Camera 1 video data by reviewing total vehicle volume and vehicle classification per lane. The video data from Camera 2 was analyzed by reviewing data frame-by-frame and identifying the total number of occlusion instances during the test period. The analysis was accomplished by S\*R engineers at the S\*R facility in Dayton, Ohio.

## 4. RESULTS

The analysis of this data was based on a total elapsed time of Camera 1 (53 minutes). This allows for consistent data to be analyzed from both cameras. Review of the video data demonstrates that high volume traffic distributed over four lanes produced a low possibility of full occlusion. Full occlusion is defined as one vehicle axle (tire) masking an axle of a vehicle(s) in the subsequent lane(s). As can be seen from the data collected in this study (Table 1 and Table 2), the aggregate probability of full occlusion is approximately 4.21%. A detailed statistical analysis of the data is provided in subsequent sections.

### 4.1 VIDEO DATA

Slow motion and frame-by-frame analysis of Camera 2 video data produced a great number of high resolution, still frames of potential and actual occlusions. S\*R engineers used this data to calculate the overall total occlusion frequency per lane. Error values have been assessed for each camera and its respective data evaluation.

**Table 1. Traffic Volume, I-275 East - Exit 46, Test Site (4 Lanes).**

Classification	Configuration	Lane 1	Lane 2	Lane 3	Lane 4	Totals
Class 1	Motorcycle	0	1	1	0	2
Class 2	Passenger Car	446	489	1,037	691	2,663
Class 3	Pickup/Van	202	232	399	291	1,124
Class 4	Bus	1	0	0	0	1
Class 5	2 axle, Single Unit, dual rear tire	14	24	18	2	58
Class 6	3 axle, Single Unit	0	7	10	2	19
Class 7	4(+) axle, Single Unit	0	1	7	0	8
Class 8	4(-) axle single trailer combo	0	2	2	0	4
Class 9	5 axle single trailer combo	9	65	35	1	110
Class 10	6(+) axle single trailer combo	0	0	0	0	0
Class 11	5(-) axle multi trailer combo	0	0	0	0	0
Class 12	6 axle multi trailer combo	1	1	0	0	2
Class 13	7(+) axle multi trailer combo	0	0	0	0	0
Run Time (min.)	<b>Totals</b>	<b>673</b>	<b>822</b>	<b>1,509</b>	<b>987</b>	<b>3,991</b>

53.73

Table 1 outlines the statistical data collected over the fifty-three (53) minutes of video. This data was tabulated to provide an indication of traffic flow during the test. As can be seen from this data, traffic volume was not identical over all four lanes. Lane 3 produced a volume of traffic over 50% higher than any other lane. Thus, one can intuitively expect to see most of the occlusion instances related to Lane 3.

Table 2 defines the number of *actual* occlusions witnessed for each lane configuration. Lane configuration is defined as the lane in which the occluding vehicle(s) is located in reference to the lane in which the missed detection(s) occurs (e.g. "1 and 2" is stated as Lane 1 occluding Lane 2).

**Table 2. Witnessed Occlusions by Lane Configuration.**

Lane Configuration	Actual Occlusions
1 and 2	5
1 and 3	12
1 and 4	0
2 and 3	26
2 and 4	4
3 and 4	22
1, 2, 3, and 4	0
1, 2, and 3	0
1, 2, and 4	0
2, 3, and 4	1
1, 3, and 4	1
<b>Totals</b>	<b>71</b>

## 4.2 STATISTICAL ANALYSIS

This section describes the statistical analysis basis used to calculate the probability of occlusion for this study.

### 4.2.1 PROBABILITY OF LANE OCCUPANCY

We can initially define the probability of lane appearance as ( $P_i$ ) by,

$$P_i = \frac{N_i}{S},$$

where  $N_i$  is the total number of vehicles in Lane  $i$  for the specified period, and  $S$  is the total number of vehicles in the sample. This is the first step in determining the overall probability of full occlusion for each lane. Table 3 outlines the probabilities for lane occupancy produced by the previous equation.

Table 3. Lane Occupancy Probabilities.

Lane ( i )	Probability
Lane 1	16.86%
Lane 2	20.60%
Lane 3	37.81%
Lane 4	24.73%

#### 4.2.2 PROBABILITY OF MULTIPLE VEHICLE/MULTIPLE LANE OCCUPANCY

By defining all events to be independent of one another, we can characterize the probability that vehicles are simultaneously in adjacent or neighboring lanes (e.g.  $P_1$  and  $P_2$ , probability of Lane 1 and Lane 2) by,

$$P(i \cap j) = P_i \cdot P_j.^3$$

This equation yields the following results as outlined in Table 4.

Table 4. Simultaneous Lane Occupancy, Lane Probabilities.

Basis $P_{ij}(i \cap j)$	Probability
$P_{1,2}(1 \cap 2)$	3.47%
$P_{1,3}(1 \cap 3)$	6.38%
$P_{1,4}(1 \cap 4)$	4.17%
$P_{2,3}(2 \cap 3)$	7.79%
$P_{2,4}(2 \cap 4)$	5.09%
$P_{3,4}(3 \cap 4)$	9.35%
$P_{1,2,3,4}(1 \cap 2 \cap 3 \cap 4)$	0.32%
$P_{1,2,3}(1 \cap 2 \cap 3)$	1.31%
$P_{1,2,4}(1 \cap 2 \cap 4)$	0.86%
$P_{2,3,4}(2 \cap 3 \cap 4)$	1.93%
$P_{1,3,4}(1 \cap 3 \cap 4)$	1.58%

This data is read as the probability that vehicles are in Lanes 1 and 2 simultaneously is 3.47%. This tells the observer that 3.47% of the time vehicles are in both Lane 1 and Lane 2.

<sup>3</sup> Probability and Random Processes, 2<sup>nd</sup> edition, A. B. Clarke and R. L. Disney, ©1985 Wiley & Sons, Inc.

#### 4.2.3 PROBABILITY OF OCCLUSION

Utilizing the probabilities in Table 4 and the information obtained from the video, we can calculate the probability of *actual* occlusion by using the following formula

$$P_{occ}(i) = \frac{\# \text{ occlusions in } i}{S \cdot P(i \cap j)}$$

Table 5 shows the probability of actual occlusion per lane based on video data and observed traffic configurations. Special conditions have been identified in terms of traffic configurations that may cause other effects on occlusion rate. These conditions include such cases as Lane 1 occluding Lanes 2 and 3 simultaneously  $\{P(1 \cap 2 \cap 3)\}$ , or Lane 2 occluding Lanes 3 and 4 simultaneously  $\{P(2 \cap 3 \cap 4)\}$ . An error rate of  $\pm 1\%$  has been assessed to these values to cover all analysis errors induced by the video data collection and review process.

**Table 5. Actual Occlusion Probabilities Based on Video Data.**

Basis $P_{occ}(i \cap j)$	Occlusion Rate
$P_{occ}(1 \cap 2)$	3.60%
$P_{occ}(1 \cap 3)$	4.71%
$P_{occ}(1 \cap 4)$	0.00%
$P_{occ}(2 \cap 3)$	8.36%
$P_{occ}(2 \cap 4)$	1.97%
$P_{occ}(3 \cap 4)$	5.90%
$P_{occ}(1 \cap 2 \cap 3 \cap 4)$	0.00%
$P_{occ}(1 \cap 2 \cap 3)$	0.00%
$P_{occ}(1 \cap 2 \cap 4)$	0.00%
$P_{occ}(2 \cap 3 \cap 4)$	1.30%
$P_{occ}(1 \cap 3 \cap 4)$	1.59%
Aggregate $P_{occ}$	4.21%

Thus, from Table 5, it can be concluded that the overall probability of occlusion over a multiple lane (i.e. four) roadway exhibiting the traffic flow characteristic of this study will warrant an occlusion factor of 4.21%. Due to a more concentrated traffic volume in lanes 3 and 4, a higher occlusion rate was witnessed for these lanes. Although this rate is higher the initial anticipations, the occlusion rate found in this study does not deprecate the overall performance of the ORADS system to a level that is unacceptable. Unacceptable limits would be in the 10% or greater range.

#### 4.3 VIDEO FRAMES ANALYSIS

The illustrations in Figure 1 provide a representation of *potential* occlusion instances identified during analysis of the video. These frame captures represent potential occlusion cases in which a large portion of a wheel is masked by a wheel in the adjacent lane. Although these instances have been marked as

potential occlusion cases, the overall blockage would not be significant enough to constitute a missed detection.

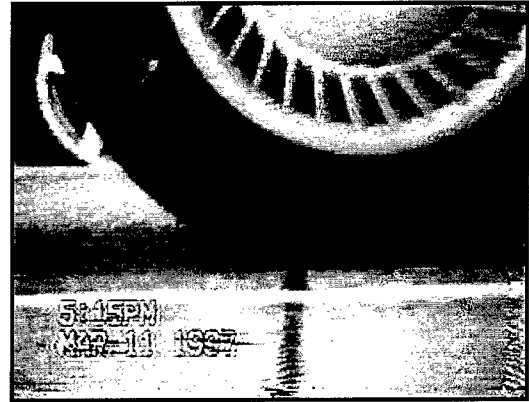
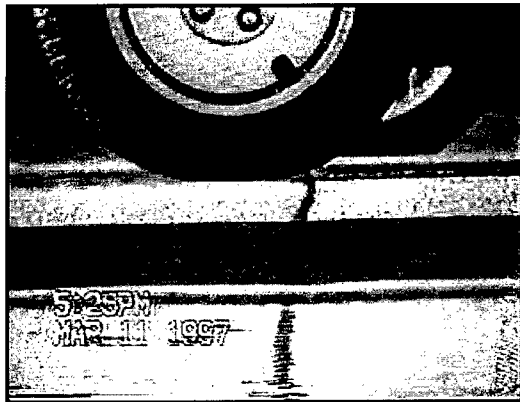


Figure 1. Potential Occlusions.

Figure 2 illustrates *actual* occlusion instances. These frame captures present an actual occlusion instance, defined as an instance when a wheel in the closest lane fully masks a wheel of a vehicle(s) in subsequent lane(s). In this case, the blockage is significant enough to miss detect an axle.



Figure 2. Actual Occlusions.

Figures 1 and 2 are representative frame shots that were found throughout the video. These particular frames were used because each best represents the situation of interest.

## 5. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 CONCLUSION

The data collected under this effort is immediately applicable to the Phase II ORADS design and is the key to continuing the design as proposed in the S\*R ORADS Phase II proposal.

It can be concluded from the results of this study that the error rate generated by occlusion in the ORADS system design is not significant enough to cause large amounts of data to be skewed during a traffic monitoring exercise. Current systems such as the TraqiCOMP® III, Model 241 produce error rates in the 10% range. It has been identified in previous discussion that an acceptable accuracy for traffic data obtained with existing portable monitoring systems and equipment is 90%.

Under the conditions realized in this study, an aggregate occlusion rate of 4.21% was encountered. Significant reduction in the occlusion percentage will be obtained on lower volume roads and for fewer lane samples.

## **5.2 RECOMMENDATION**

Based on the findings presented in this report, S\*R recommends continuation of the ORADS Phase II development effort.



# **APPENDIX A**

## **Lane Monitor Blockage Analysis**

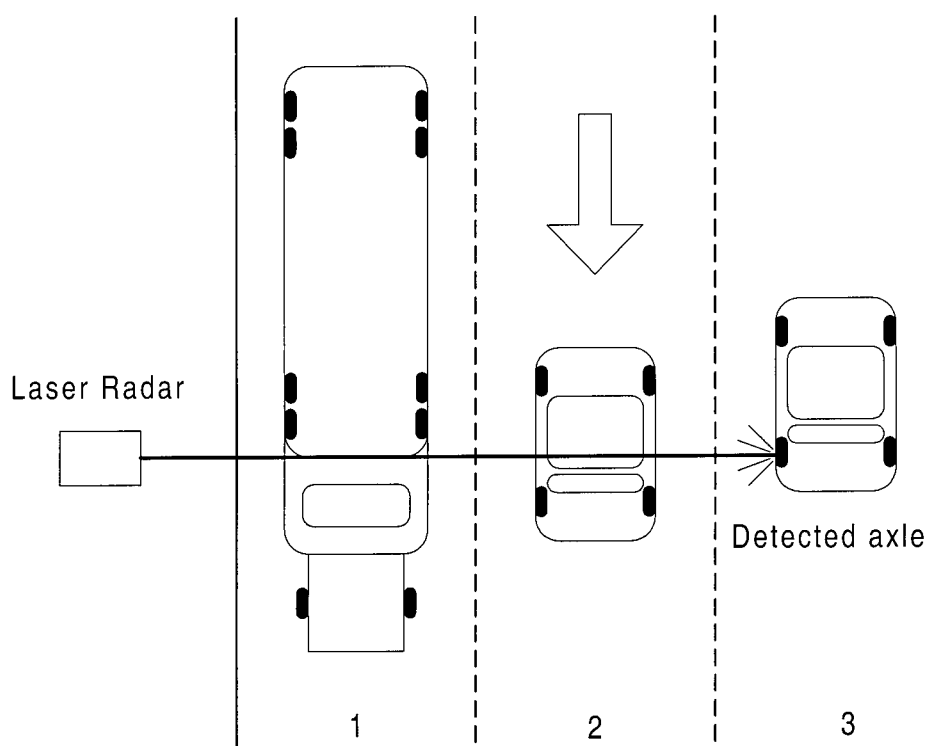
Authored by:  
**Gordon R. Little, Ph.D.**  
**University of Dayton Research Institute (UDRI)**

# Lane Monitor Blockage Analysis

Gordon R. Little

July 9, 1996

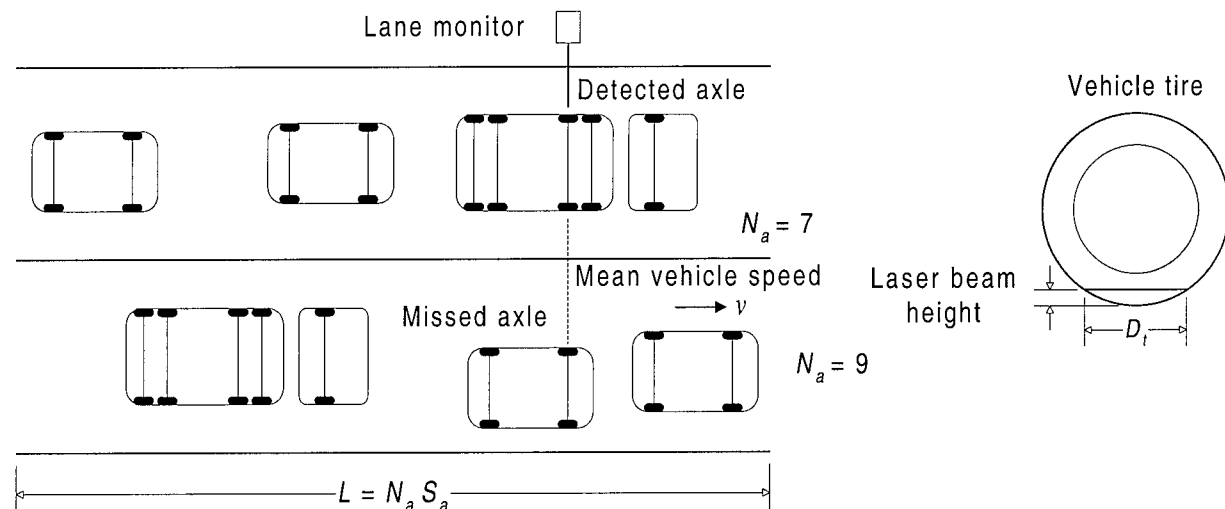
The Spectra Research optical lane monitor system uses an optical radar to count and classify vehicular traffic on multiple-lane highways. The approach, depicted in Figure A 1, directly senses vehicle axles by detecting laser pulses that are reflected from the tires of passing vehicles. Counting and classification accuracy is maintained even under heavy traffic conditions by using time-of-flight to unambiguously assign a lane to each returned pulse. The ability to separate counts by lane is an important improvement over pneumatic tube traffic monitors.



**Figure A 1. Laser Radar Traffic Monitor.**

One concern that has been raised is the possibility of count errors due to blockage of traffic in the more remote lanes by tires of vehicles in the near lanes. This brief note assesses this situation and derives an expression for estimating the count error rate due to this effect. The analysis predicts a vehicle error rate of 2% for per-lane traffic density of 2200 vehicles per hour with an average speed of 60 mph on a three-lane highway.

We start with a simplified analysis that estimates the mean error rate in counting axles in one traffic lane that is blocked by another as illustrated in Figure A 2. A count error will occur when two conditions occur: (1) there is an axle in the first lane that blocks the beam and (2) there is simultaneously an axle in the second lane that would otherwise be detected. The probability of these two conditions occurring together is the product of the probabilities for the separate "conditions". These probabilities are approximately equal if traffic distributions in the two lanes are identical.



$L$	Length of sampled traffic	$D_t$	Effective tire width	
$N_a$	Number of axles in length $L$	$P_{sl}$	Single-lane probability	$P_{sl} = \frac{N_a D_t}{L} = \frac{D_t}{S_a}$
$S_a$	Mean axle spacing			

Figure A 2. Elements of the Blockage Probability.

As indicated in Figure 2, we may estimate the single-lane probability  $P_{sl}$  as the ratio of the tire width  $D_t$  to the mean axle spacing  $S_a$ :

$$P_{sl} = \frac{D_t}{S_a}$$

and the axle error probability  $P_a$  as:

$$P_a = \frac{D_t^2}{S_a^2}$$

Taking the tire width at the laser beam height to be 1.5 ft and the mean axle spacing to be 30 ft, we compute an axle error probability of 0.0025. Note that this assumed axle spacing with a mean traffic speed of 30 mi/hr corresponds to a traffic rate of 2640 vehicles per hour.

The above analysis tells us the probability of axle count error for the second lane of a two-lane highway configuration. To obtain the more relevant vehicle count error for realistic highways requires consideration of the number of axles per vehicle and the

impact of multiple lane blockages. We start by expressing the total number of correct vehicle detections  $N_{T,C}$  in some counting time interval  $T$  as

$$N_{T,C} = N_1 + (N_2 - N_{2,1}) + (N_3 - N_{3,1} - N_{3,2}) + \dots$$

where  $N_i$  represents the total number of vehicles in lane  $i$  that pass the monitor in the counting interval and  $N_{i,j}$  represents the number of errors for vehicles in lane  $i$  due to blockage from vehicles in lane  $j$ .

We may express in terms of two-lane vehicle count error probabilities  $P_{i,j}^v$  as

$$N_{T,C} = N_1 + N_2(1 - P_{2,1}^v) + N_3(1 - P_{3,1}^v - P_{3,2}^v) + \dots$$

Introducing the total number of vehicles

$$N_T = N_1 + N_2 + N_3 + \dots,$$

the error count rate is

$$E = \frac{N_T - N_{T,C}}{N_T} = \frac{N_2 P_{2,1}^v + N_3 (P_{3,1}^v + P_{3,2}^v) + \dots}{N_1 + N_2 + N_3 + \dots}$$

We now must relate vehicle error probabilities to axle count error probabilities. A conservative approach is to declare that missing any vehicle axle results in an error for a vehicle. In this case, we have

$$P_{i,j}^v = n_a P_a$$

where  $n_a$  is the average number of axles per vehicle.

To obtain a reasonably tractable relation for the vehicle count error rate, it is convenient to assume that the vehicle rates, mean speeds and vehicle type distributions are the same for all lanes of the highway. In this case  $E$  becomes:

$$E = \frac{n_a P_a (1 + 2 + \dots + m_L - 1)}{m_L} = \frac{n_a (m_L - 1)}{2} P_a$$

where  $m_L$  is the number of lanes in the highway. Expressing the mean axle spacing in terms of the mean vehicle speed  $v$  and the per-lane vehicle rate  $\dot{N}$ .

$$S_a = \frac{v}{n_a \dot{N}},$$

we find

$$P_a = \left( \frac{n_a \dot{N} D_t}{v} \right)^2$$

and

$$E = \frac{n_a (m_L - 1)}{2} \left( \frac{n_a \dot{N} D_t}{v} \right)^2$$

The above relation is the major result of this analysis. If we assume a three- lane highway, a per-lane vehicle rate of 2200 vehicles per hour, a mean vehicle speed of 60 mph, a mean tire diameter of 2 ft, and an average of three axles per vehicle, a vehicle error rate of 2% is predicted.

Two comments should be made about this result. First, the formula is conservative in that we have used the tire diameter to characterize the blocking probability for the hidden tire. In fact, the laser radar will detect the hidden lane tire as long as there is an appreciable offset  $O$  from the blocking tire. There will be full detection, for example, if the offset is equal to the laser beam diameter (e.g. 2"). Accordingly, the  $D_t^2$ , term should be replaced by  $D_t O$ . With this modification, the predicted error rates are reduced by an order of magnitude.

